An Evolution of ILI MFL Specifications for Corrosion and Pinholes – and Some Approaches for the Future

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Abstract

Since the introduction and validation of ILI Magnetic Flux Leakage (MFL) specifications for pinhole corrosion defects more than 10 years ago, industry has benefited greatly from gained experience with such capabilities.

This paper provides a brief review of the nature of “pinhole” ILI performance particularly for MFL inspection including the influences in providing accurate inspection results - as well as technical development steps to date regarding pipeline corrosion inspection and reporting.

The interpretation of API 1163 guidance has played a role in such perceptions and specifications that will be outlined in this paper. Similarly, the nature of “hard boundaries” behavior related to corrosion type categories (the “POF” categories”) plays a role. The need to address such perceptions will be described and real examples of features will be presented with case examples of isolated and complex corrosion morphologies.

Industry feedback, both in the field measurement improvements and volume of feedback features, has led to further improvements and possibilities beyond current ILI conventions. The paper will then describe with examples of alternatives and with some description of new conventions of ILI performance for the future.

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Introduction

Within the history of the pipeline integrity industry, the term “pinhole” defect refers to small diameter corrosion with potential to lead to a leak. Pinholes are problematic for both gas operators and liquid operators as they can be the primary threat for leaks and can affect the pressures severity assessment of the defect if several pinholes cluster together to form a longitudinal feature. It is also considered a prime threat and result from MIC (microbiologically induced corrosion) mechanisms. With the progression of inline (ILI) pipeline inspection technology capabilities, it enabled focus to pinhole defects.

With the introduction of statistical & quantitative ILI sizing results in the 1980s , there remained a gap to progressing as an industry. Namely a common set of conventions and guidelines for 1) assessing ILI performance results and specifications (eg +/-10% 80% of time) and a common reference for defects of interest amongst pipeline integrity practitioners (e.g. variants and categories for corrosion).

In the 1990s, the European Pipeline Operators Forum (POF) published a reference specification for themselves and for ILI vendors. [Ref 1]. Within industry at the time ILI (MFL) predicted results were observed to vary with feature spatial dimensions which could be traced back to fundamental physics of MFL and specific sensor system (tool) design choices such as resolution (axial direction and circumferential direction) and magnetic field components (axial, radial, circumferential).

The POF group set a reference definition of reporting and criteria so as to have consistency in ILI reporting and in fundamentals of vendor technology capabilities against primary influences to ILI specifications. This reference specification included a requested disclosure by vendors of design factors like magnetic field strengths and influence of speed in MFL techniques. (Ultrasonics wall measurement methods had similar disclosures of key functional parameters such as UT frequency, stand off and sensor size).

More distinctly, the reference specification defined and described subset classifications for corrosion as the primary threat of interest at the time. The definition is outlined in Figure 1.

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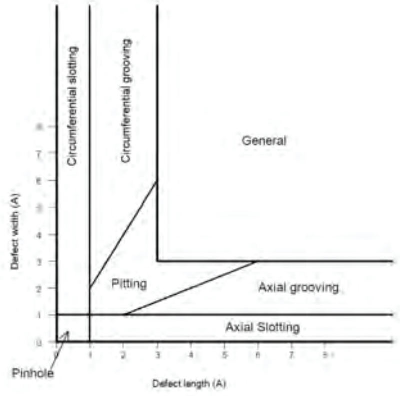

Metal-loss type	Definition	Reference point for the POD in terms of L x W
General:	{[W = 3A] and [L = 3A]}	4A x 4A
Pitting:	{([1A = W < 6A] and [1A = L < 6A] and [0.5 < L/W < 2]) and not ([W = 3A] and [L = 3A])}	2A x 2A
Axial grooving:	{[1A = W < 3A] and [L/W = 2]}	4A x 2A
Circumferential grooving:	{[L/W = 0.5] and [1A ≤ L < 3A]}	2A x 4A
Pinhole:	{[0 < W < 1A] and [0 < L < 1A}	½A x ½A
Axial slotting:	{[0 < W < 1A] and [L = 1A]}	2A x ½A
Circumferential slotting:	{[W = 1A] and [0 < L < 1A]}	½A x 2A

	General metal-loss	Pitting	Axial grooving	Circumf. grooving
Depth at POD=90%				
Depth sizing accuracy at 80% confidence				
Width sizing accuracy at 80% confidence				
Length sizing accuracy at 80% confidence				

Figure 1: 1998 POF Corrosion Categories

With each category there is a defined feature size as the reference point. Hence with pinholes and the general reference of wall thickness "A" = 10mm , it introduces a convention of ½ A as the reference dimensions for pinholes. Hence ILI MFL specifications started to include clarifications for defect reference diameters such as ">5mm" vs "<5mm". Similarly, a 25mm diameter defect in very thick wall, (such typically offshore and/ or Class 4 locations) would be categorized as a pinhole for wall thicknesses >= 25mm. Some review of thicker wall experiences is described below.

In parallel, there was a increasing need amongst operators and ILI providers also for the standardization of ILI performance and calculations which, through cross-industry collaborative efforts, is available today as the API 1163 standard with its 1st edition published in 2005. [Ref 2]

By 2009, ILI technology had evolved to allow for the distinction of pinholes, slots and grooves to be more formalized and so were expanded within the POF specification, alongside the conventional pitting and general corrosion category types as shown in Figure 2. [Ref 3]

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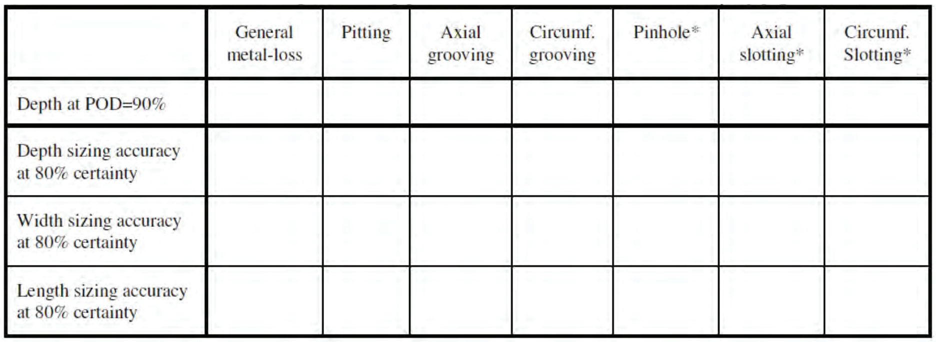
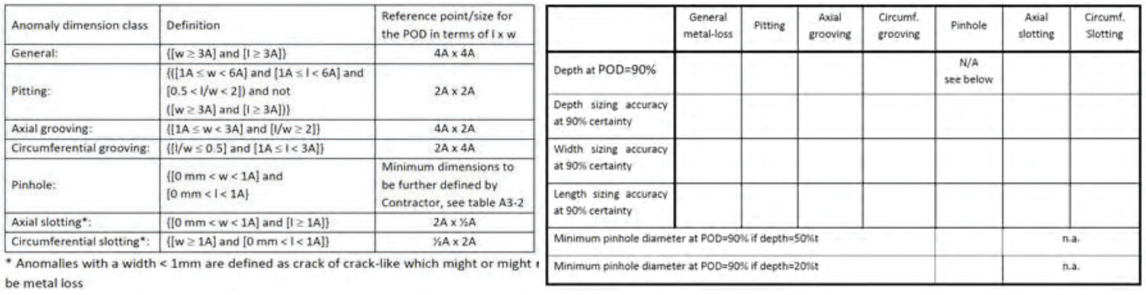


	General metal-loss	Pitting	Axial grooving	Circumf. grooving	Pinhole*	Axial slotting*	Circumf. Slotting*
Depth at POD=90%							
Depth sizing accuracy at 80% certainty							
Width sizing accuracy at 80% certainty							
Length sizing accuracy at 80% certainty							

Figure 2. 2009 POF Corrosion Categories

Over time, the POF group continued to recognize improvements were occurring with pinhole specifications but still were dependent on feature size and similar factors. In 2016, additional clarifications for pinhole specifications [Ref 4] were added such as minimum diameters at different depths as expressed in Figure 3. (This is also in the most recent 2021 POF publication)



Anomaly dimension class	Definition	Reference point/size for the POD in terms of l x w
General:	{[w ≥ 3A] and [l ≥ 3A]}	4A x 4A
Pitting:	{([1A ≤ w < 6A] and [1A ≤ l < 6A] and [0.5 < l/w < 2]) and not ([w ≥ 3A] and [l ≥ 3A])}	2A x 2A
Axial grooving:	{[1A ≤ w < 3A] and [l/w ≥ 2]}	4A x 2A
Circumferential grooving:	{[l/w ≤ 0.5] and [1A ≤ l < 3A]}	2A x 4A
Pinhole:	{[0 mm < w < 1A] and [0 mm < l < 1A}	Minimum dimensions to be further defined by Contractor, see table A3-2
Axial slotting*:	{[0 mm < w < 1A] and [l ≥ 1A]}	2A x ½A
Circumferential slotting*:	{[w ≥ 1A] and [0 mm < l < 1A]}	½A x 2A

* Anomalies with a width < 1mm are defined as crack of crack-like which might or might

be metal loss

	General metal-loss	Pitting	Axial grooving	Circumf. grooving	Pinhole	Axial slotting	Circumf. Slotting
Depth at POD=90%					N/A see below		
Depth sizing accuracy at 90% certainty							
Width sizing accuracy at 90% certainty							
Length sizing accuracy at 90% certainty							
Minimum pinhole diameter at POD=90% if depth=50%t						n.a.	
Minimum pinhole diameter at POD=90% if depth=20%t						n.a.	

Figure 3. 2016 POF (also in most recent 2021 version)

Design Elements of a MFL system for a pinhole specification

As described previously in 2010 [Ref 5], the design of a new MFL ILI system was then tasked to achieve pinhole sizing specifications and also for other defect types [Ref 6]. Underlying the design were the principles of Detectability and Measurability. Aspects of the original design work were outlined in 2014 [Ref 7] within the validation achieved with a partnering pipeline operator. Other efforts mentioned included modelling and a design study that included “ideal” entitlement considerations and definitions for signal to noise (SNR) , sampling influences and signal (aliasing) both for detection and signal characteristic measurement, and applicable sizing model architectures (eg the approach for sizing models of pitting may not directly apply) [Ref 8]

As presented, pinhole defects diameters of 2-3mm were validated as consistently detected and, for sizing specifications stated at the time, 90% performance certainties for defect diameters 5-10 mm. The 2010 and 2014 papers also briefly highlighted Detectability as distinct from Measurability for which some further insight is described here.

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As highlighted in very early work, the axial MFL signal component tends to mimic the spatial shape of (general) corrosion while the radial MFL signal component demonstrates a high SNR response particularly for sharp transitions at the defect's edges. [Ref 9].

As part of the MFL platform tool design, the magnetizer's magnetic field strength and sensing configuration were considered for cases of thicker wall (offshore) inspection with pinhole specifications.[Ref 5,7,10]. Within the MFL inspection technique, the "leakage" signal response from a defect is inherently spread over a larger spatial area than that of the feature area itself. Detection and measurability of the signal is not set to the feature size itself, but to the sampling resolutions required to achieve reliable detectability of the signal and measurability of the signal characteristics (such as Amplitude, signal duration. Etc).

Figure 4 illustrates the distinction of Detectability vs Measurability for a small pinhole feature as influenced by the tool's sampling resolutions which led to the selection of an optimal axial and circumferential resolution. Figure 4a and 4b would be reliably detected but experience poorly measured signal parameters thus limiting the entitlement of sizing accuracies. Figure 4c is both detectable and measurable for signal parameters with minimal reproducibility error. Figure 4d represents the "oversampled" case which is not practical on an operational ILI tool. The feature signal is readily detectable and measurable but also contains a large redundancy of data that provides little to no added value to the entitlement to sizing accuracy from signal parameters. Figure 4c then represents practical and optimal selection for tool sampling resolution.

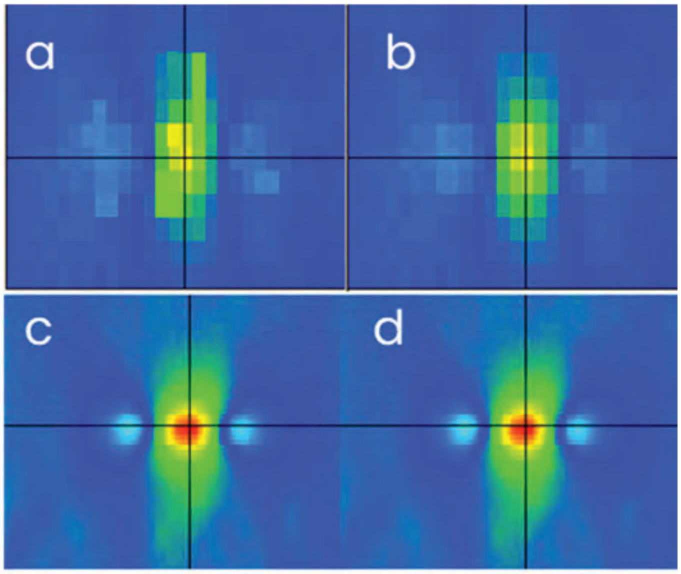

Figure 4. MFL signal with (down-sampled) simulation of resolutions illustrating Detectability vs Measurability

Using the examples of Figure 4, the selection process of optimal sampling resolutions for pinholes is readily handled for each of the MFL field signal components (Axial, Radial, Circumferential) and

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equivalent Detectability and Measurability assessments were achieved as shown in Figure 5 and 6. As expected, pinhole Detectability for a given defect depth is achieved for smaller diameters than Measurability (of signal parameters) but what is also important to note is the advantage the radial field component (as used in triaxial MFL tools) has to both detection and measurement at lower depths.

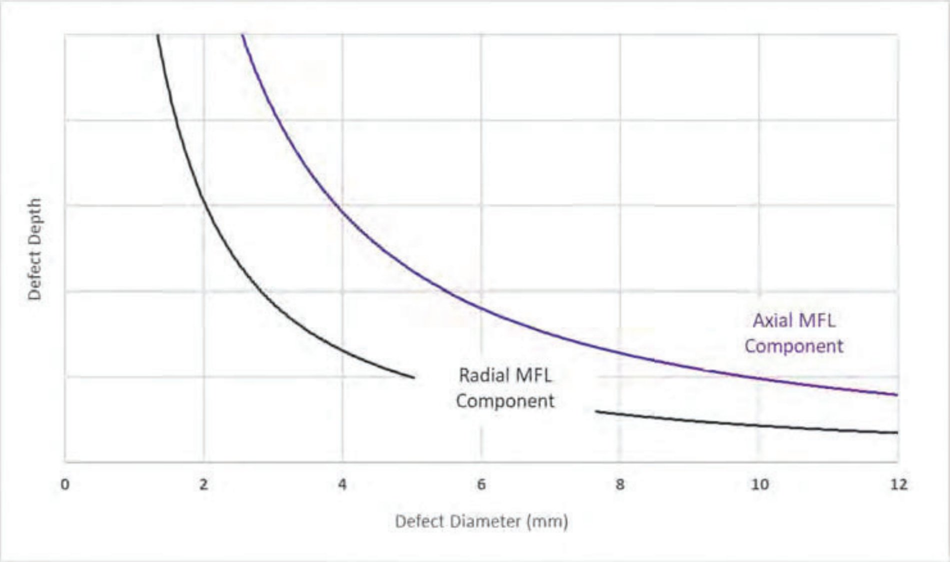

Figure 5. Detectability per Axial and Radial MFL magnetic field components vs defect diameter

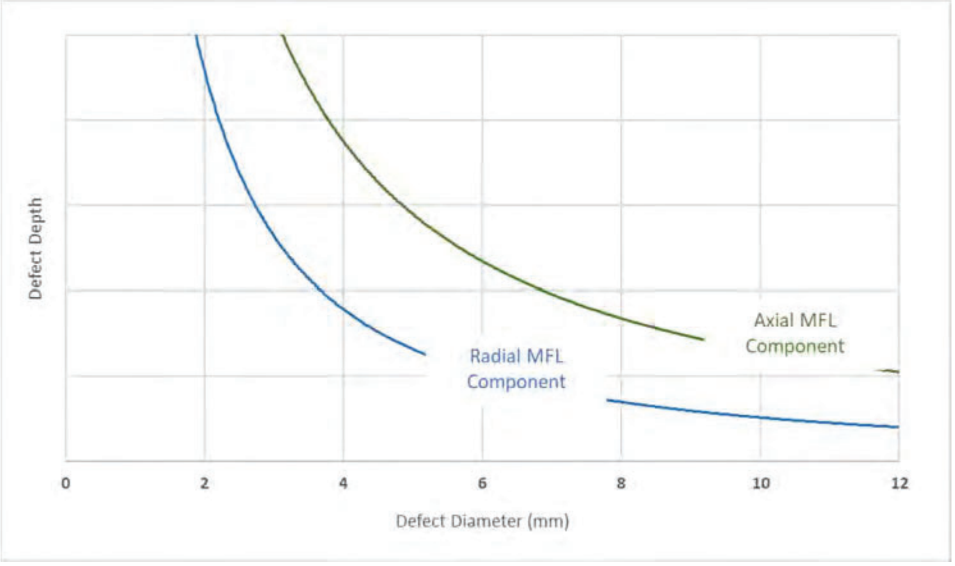

Figure 6. Measurability per Axial and Radial MFL magnetic field components vs defect diameter

Aspects of assessing performance

As previously described [Ref 11], it was highlighted that defects of interest and features of concern for failure are often associated with complexity. Fundamentally within the experiences of industry for complex corrosion, there are core differences in the inspection and evaluation of an the isolated defect vs an interacting (cluster) corrosion defect. (Figure 7) The variability and permutations of complex features is a primary influence to the causes of sizing outliers. Additionally, there has a been an exponential increase in field data feedback. Prior to more common and widespread use, field NDE reports may still have consisted of photos and field notes.

Minimizing the occurrences of outliers requires re-evaluation of industry requirements for ILI tools and evolving their related performance specifications. Primarily as a goal for reliable interpretation regardless of influences from pipe operations, feature size or surrounding environment.

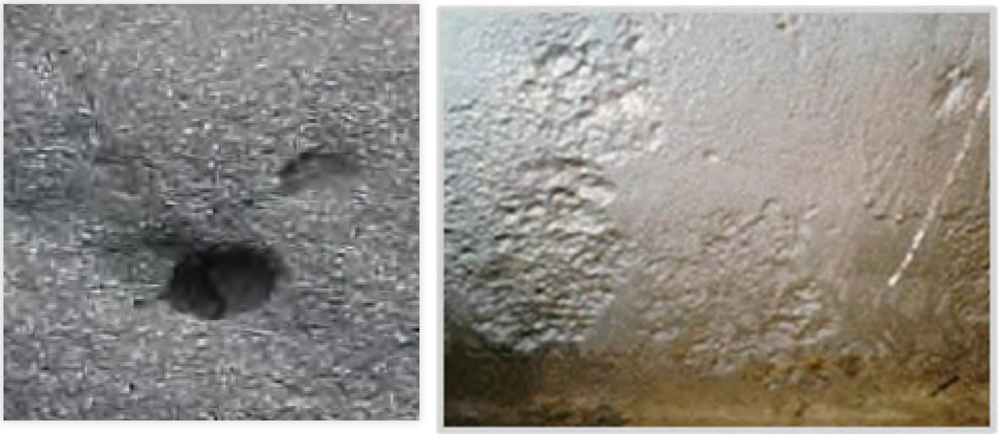

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Figure 7. Isolated defect vs complex corrosion area

For external corrosion, field data today is generally provided in high resolution topological grid formats such as from laser scanning techniques. For internal corrosion, grid mapping such as probe ultrasonics was typically used. Availability of digital high resolution field data itself does not directly address the matching between field NDE and ILI predicted feature results, particularly for using the POF/1163 categories as reference.

Reliable and automated matching methods were required to be developed to manage the scale of the 1000s of datasets while ensuring alignment at millimetre level and its impact on the assessment of detection and sizing performance. [Ref 12]

Inherent limitations arise in the verification of true “identified pinholes between NDE and ILI for complex corrosion areas (clusters). In basic image processing terms, it’s attempting to ensure a few pixels from one image aligns with a few pixels of another image while also expected to clearly identify the object. When including the detection and measurement characterization of pinholes within the scope of field NDE, then the consideration of the NDE comparison and the limits of its resolution is prudent.

Pinhole Sizing Performance

Artifacts from definitions conventions

Before discussing and reviewing sizing performance of ILI, it is relevant to highlight some "artifacts" that arise from the conventions in assessing integrity from ILI results. A primary one is the "discontinuity" at the corrosion category "boundaries". In the theme of this paper, the convention "A x A" for the boundary between pinholes and pitting can result in a discontinuous tolerance spec, while the boundaries themselves are subject to tolerances on the order of magnitude of their size. If using ""A" as 10mm – then pinholes of "precise" 9.99mm would relate to sizing specification of +/-15% depth while a pit of "precise" 10.01mm is related to +/-10%.

The ramifications of this artifact become at least twofold: 1) in assessing performance there will be an overlap of "misclassified" features in corrosion categories so the appropriate tolerances for a given feature can cause confusion and 2) an operator must still consider an appropriate sizing tolerance to apply in integrity and risk assessment calculations.

Within the results presented in the next section, the data shown primarily relates to feedback as provided from North American (NAM)pipe operators. In context of the POF "10 mm" reference, the wall thicknesses of this population were < 12mm . (As was the earlier validation work [Ref 7] that occurred in Europe). There are two aspects to this: 1) the physics of the MFL technique realizes stronger magnetic fields and signal responses in thinning wall thicknesses, leading to 2) more optimal conditions for detection and measurement for smaller diameter pinholes than the 10mm convention

It is also noted that there are tendencies in industry to label and group performance "collectively" simply by its technology basis, eg "MFL tools" when in actuality, performance is directly linked to the system design utilized, technologies and methods employed, and the collaboration between the operator and the ILI service provider.

Baker Hughes MFL system performance for pinholes

For the time period 2014- 2019, field feedback for complex corrosion (and thus assessing pinhole performance) was still a mixture of formats and resolutions. Verified and matched data was hence limited. Results for verified pinholes are shown as in Figure 8 for 5-10 mm actual diameter. +/- 15% was achieved 81% of the time.

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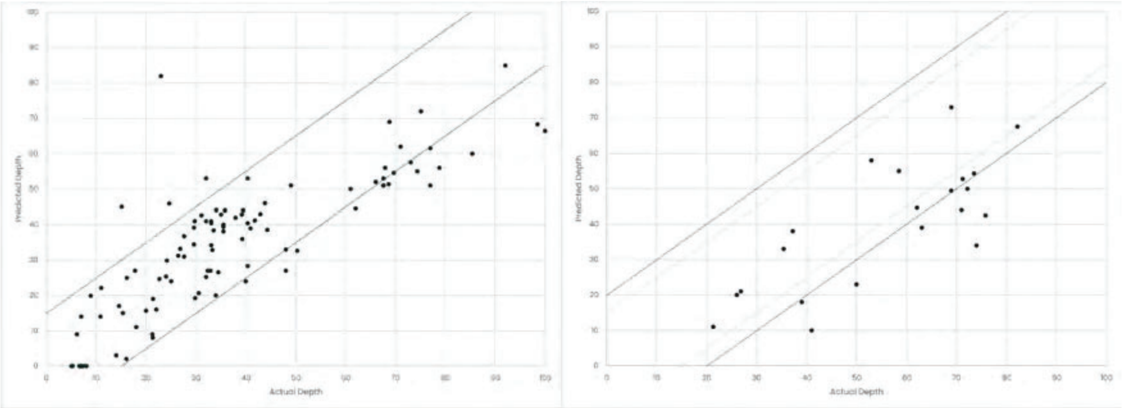


Figure 8. 2014-2019 Results for verified pinholes

(a) 5-10mm in diameter and (b) <5 mm in diameter

In other circumstances, we received field feedback that identified a pinhole with a depth but did not have length or width spatial dimensions provided to be able to affirm formally within the POF pinhole category definition. In many cases, field notes provided indicated the pinhole was identified but in a larger complex area of many corrosion features which widely understood to be more challenging than isolated features or artificially created pull test data which is commonly used to present validation of performance. Results of this dataset are shown in Figure 9. The results performance was +/-15 % , 92% of time.

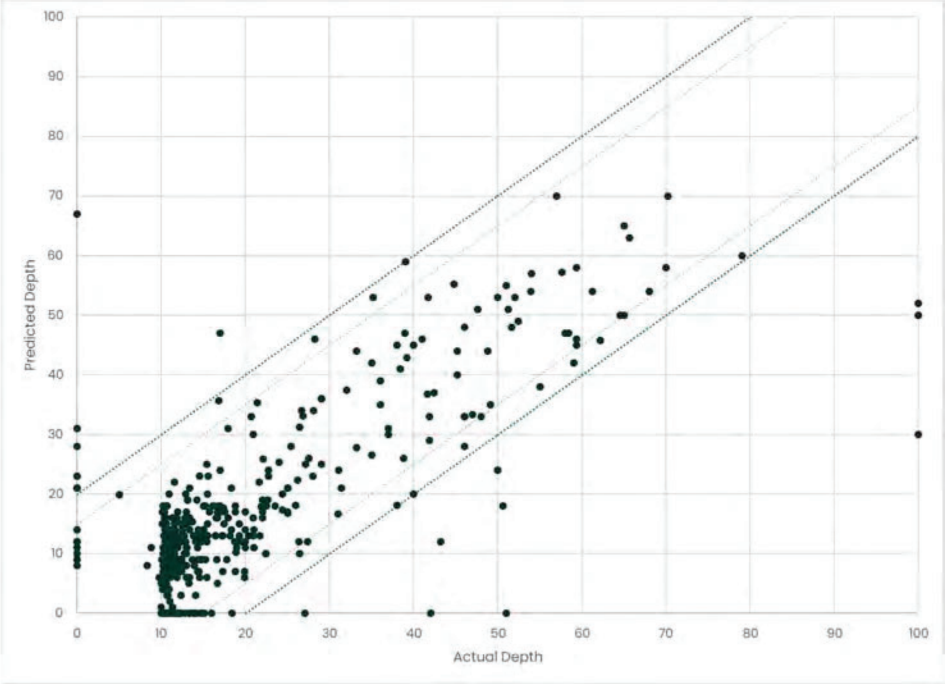
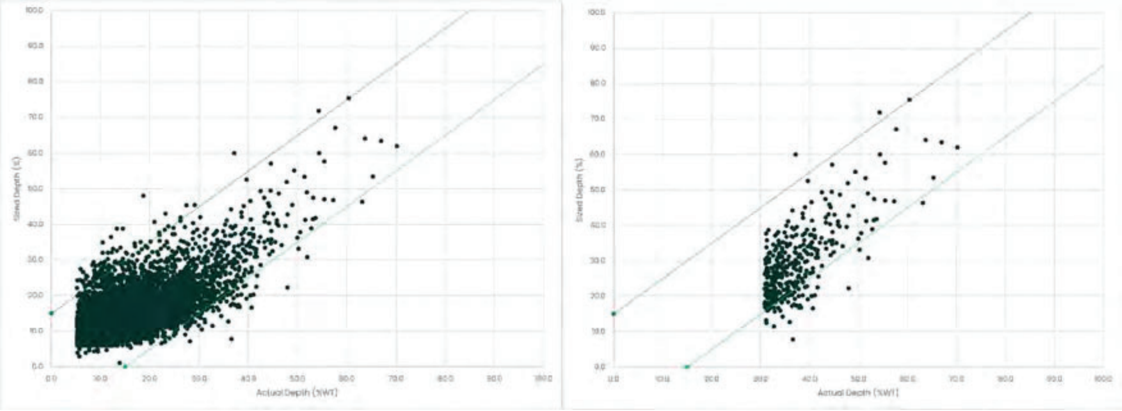


Figure 9. Results for field-identified “pinholes” (without specified L, W dimensions)

As observable in Figure 8 and 9, while the overall predictive performance is noteworthy, there were (non-conservative) outliers identified. However, in context, the dig and resulting feedback data collected were because of some ILI identified conditions that triggered dig criteria for the respective operators. The 3 outlier leak features were part of more complex areas but unclear as to actual localized dimensions.

In assessing Baker Hughes pinhole corrosion sizing performance of a more recent period, Figure 10 shows unity plot performance for the entire pinhole population and then with some focus on > 30% WT actual depth. For the > 30% WT data subset, the depth tolerance performance was +/-15% with 89% certainty.



(a) (b)

Figure 10. Recent performance study – (a) full (pinhole) population (b) subset with actual depths > 30%

Alternative Forms of Inspection Specifications

Predicted Tolerances

Results were more recently presented of a collaborative effort between Baker Hughes and an operator for exploring the feasibility and value of "Predicted" tolerances [Ref 13].

In this approach, sizing models are developed around achieving a stated tolerance certainty. Individual predicted sizing tolerances are provided for a given feature along with its predicted dimensions (independent of POF or other convention references). As described, the approach was shown to notably reduce inherent conservatism. Predicted tolerances are stated for each reported feature in an ILI inspection listing.

Mathematically, and systematically, there is an underlying logic to the improvements. Conventional definitions (POF, API 1163) were primarily to establish some common baselines and based in the observations of the time, correlations are still factual such as varied MFL signal behaviour, between

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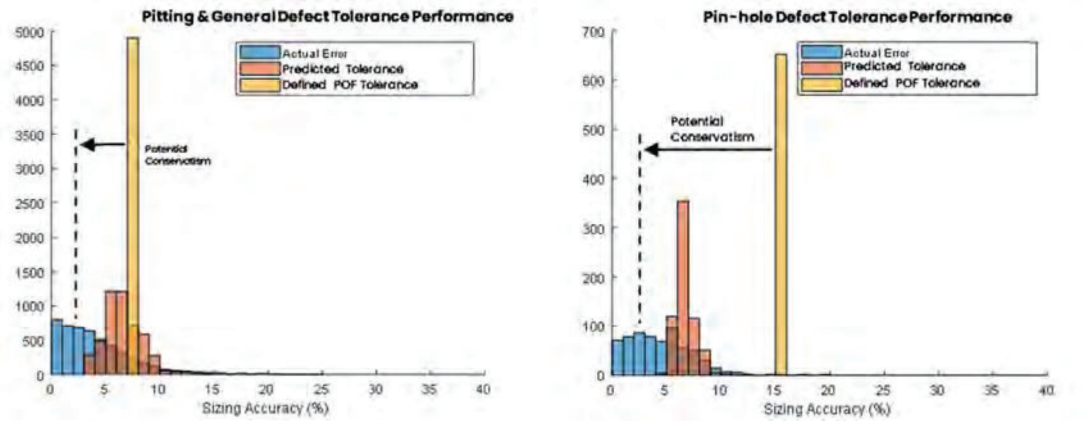
axial slots, circumferential slots, pinholes, and pits, etc, and hence sizing performance differences amongst them. However, in adopting the convention definitions, resulting ILI sizing models then also adopted constraints in that it grouped populations of defects signals when there are other influencing parameters and behaviours involved.

Figure 11 shows results for Pitting & General corrosion and Pinhole defects. Within each chart, the conventional POF tolerance is shown (for the equivalent POF category determined from actual dimensions), the predicted tolerances for the set and the related actual depth sizing error population. Particularly for pinhole corrosion defects, there was a notable difference between conventional pinhole tolerances and predicted tolerances. Within the study, it was also observed that importantly, the actual length and width dimensions of a given feature were not the dominating influence on potential tolerances and improvements in depth sizing as is commonly assumed.



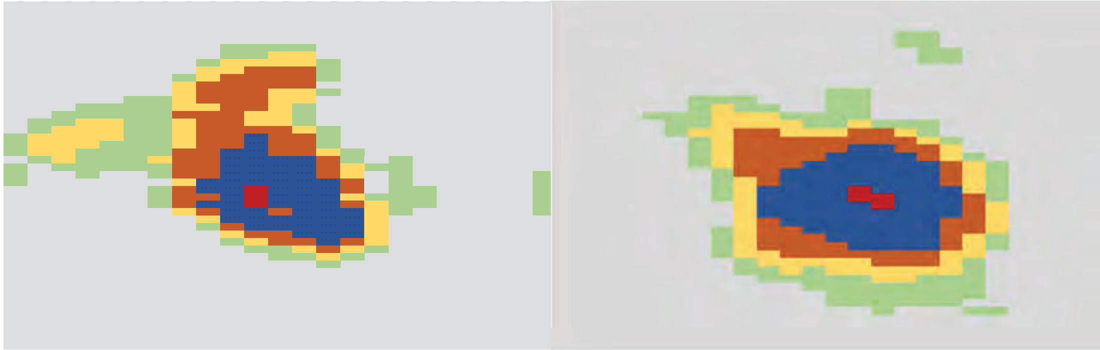
(a) (b)

Figure 11. Predictive tolerance performance at 80% confidence interval(s) for (a) Pitting & General and (b) Pinhole corrosion

Beyond predicted tolerances

As described previously [Ref 12,14], machine learning has a role in pipeline inspection and integrity. Data formats of topology of corrosion area have existed and the use of such data has been shown to allow improvements in sizing and in pipeline reliability. But industry practices have only recently defined formats for exchange [Ref 15, 16] Continued industry demand to predict corrosion topology will push development but more importantly, the more widespread adoption and use of such methods as everyday standard acceptable formats and practices.

In prior work [Ref 11], early examples were noted for the application of advanced machine learning to predict the corrosion topology (depth) from MFL signals. These methods also have promise for pinholes specifically as shown in Figure 12. Note that the x & y scale of the data grid (pixels as images) is 1mm x 1mm and color changes represent increments of 10% WT. The approach of predicted tolerances also has a role and format in direct topological prediction methods.



(a) (b)

Figure 12. Machine Learning depth prediction example for a pinhole. (a) predicted topology (b) laserscan grid

Summary

Industry specifications have been evolving to recognize and standardize conventions for ILI measurement and reporting.

Sizing performance for pinholes has been improving with increasing operator feedback. Success on performance should not be based in anecdotal examples but in verified and well documented assessments with statistically significant populations, in real-world environments.

MFL systems should be designed for optimal data collection which is not just based on axial sampling resolution . Triaxial MFL signal measurements should be considered as it provides clear advantages to optimally characterize pinhole defects.

Predicted tolerances remove performance “artifacts” resulting from boundary definitions within commonly used industry specifications. Prediction of the corrosion depth topology is developing through advanced machine learning methods.

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